The Delphinoid Ear: Anatomical and Physiological Observations

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Delphinoids have a mammalian ear that evolved on land for aerial hearing and then adapted to underwater hearing when delphinoids returned to the sea. How the delphinoid ear receives sound is of scientific interest not only because of this secondary adaptation but also because human made sound in the sea is of increasing concern relative to its potential for interference with ocean mammals. Anatomical studies on dead specimens go back more than 200 years but only recently has it been possible to do some studies of live animals with computed tomography. Behavioral audiograms have been done during the past 40 years and in that time physiological studies have also been conducted on the ear's responses to sound. This presentation will cover the physiological perspective from the standpoint of observed potentials generated by hair cells in the cochlea and observed central nervous system potentials evoked by acoustic stimuli, the behavioral perspective of auditory threshold and reaction time studies, and the anatomical perspective of specimen dissection and computed tomography of living animals.

Investigating the Effects of Sound on a Cuvier's Beaked Whale *(Ziphius Cavirostris)* Model

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Recent beaked whale stranding events associated with sonar operations catalyzed an effort to build a finite element (FE) model to simulate acoustic propagation within the body of a Cuvier`s beaked whale. This model was constructed from a recently postmorten calf of *Ziphius cavirostris*. Thus far, we have completed: (1) construction of a registration `sarcophagus` containing the specimen and specific density rods so that the scans could be calibrated and accurately reconstructed in three spaces, (2) cutting the entire sarcophagus into four manageable pieces, (3) CT scanning each piece, (4) detailed sectioning of the specimen and extraction of more than 600 samples for analysis of biomechanical properties such as acoustic velocity, attenuation, and tissue elasticity. Preliminary analysis suggests the data are robust, and consistent with the trends in structure and acoustic velocity as shown for the biosonar apparatus in other species. We are currently constructing an FE model from the empirical data that should allow us to: (1) create tools to simulate the effects of man-made sound on organs, tissue interfaces and the peripheral auditory system, (2) investigate acoustic pathway(s) through the peripheral auditory system to the ears, including the juxtaposed and hypertrophied fibrous venous plexus of the pterygoid sinuses, (3) predict sound levels within the body as a function of source intensity, frequency, range, and bearing, (4) examine mechanisms for how sound may be focused, refracted, reflected, or altered in various parts of the body. These simulations may provide insights into the factors that contribute to the stranding events of recent years.

Physical Properties of Ziphius Cavirostris Tissues from a Stranded Calf

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Recently, sonar operations have been associated with mass strandings of beaked whales; however, the mechanisms or specific causes of the strandings are unknown. To better understand how sound pressure events might affect these whales, we studied the physical properties of Ziphius cavirostris tissues. The head of a Ziphius calf was CT scanned, dissected, and nearly 300 samples were extracted. We measured longitudinal sound velocity, acoustic attenuation, density, and elasticity for each sample. Samples were classified by tissue type. Within the forehead, physical properties co-varied within tissue type, such that for the acoustic fats, average sound speed (1465 ±8.9 m/s), attenuation (3.1 ±0.5 dB/mm), and density (0.94 ±0.02 g/cm3) were minimal. Connective tissue had the greatest average sound speed (1634 ±49.5 m/s), attenuation (4.8 ±0.7 dB/mm) and density (1.09 ±0.04 g/cm3). Blubber and muscle values lie between acoustic fats and connective tissue for all three measures. This low density, low velocity core of the melon is similar to previous reports for delphinoids. We intend to determine if there is a predictable relationship between CT number and any of our physical property measurements, and construct a finite element model of the whale that may shed light on the causes of the stranding events.

Beaked Whale Heads: Is There a Smoking Sonar?

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Over 20 beaked whales died in mass strandings within the last two years. Three strandings (Bahamas, Madeira, and the Canary Islands) coincided with large scale naval exercises, raising concerns for blast and acoustic traumas. This talk focuses on the analyses of the Bahamian and Madeiran events; however, because final consensus reports are not yet available, the analyses presented are not binding nor definitive. Tissues and intact heads were examined from 9 of 15 animals, 5 of which were adequately fresh condition to warrant CT and histologic examination. No animal had conventional blast damage, but all heads had evidence of in vivo cranial trauma: intra-cochlear blood, subarachnoid hemorrhages, and ventricular clots. The hemorrhage patterns suggests inner ear structures remained intact and the cochlear aqueduct was the conduit for bloodflow between cranial and inner ear spaces. These pathologies may have compromised hearing but were unlikely to be immediately lethal. The following etiologies have similar trauma patterns: concussive acoustic trauma, barotrauma, auditory concussion, sonic booms, spontaneous hemorrhage and hyperemia, vestibular atelactasis, intraoperative birth trauma, and diathetic disease. Of these, a direct acoustic pressure event or diathethic stress response are most consistent with the stranding event and postmortem evidence.

The Influence of Phylogeny, Ontogeny and Topography on the Lipid Composition of the Mandibular Fats of Toothed Whales: Implications for Hearing

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Odontocete melons exhibit complex topographical variation in lipid composition, believed to be critical for focusing transmitted sound. However, the distributions of lipids responsible for transferring received sound through fat channels in the lower jaws to the ears are virtually unknown. We determined lipid composition at multiple sites in mandibular fats of harbour porpoises, and Sowerby's and Gervais' beaked whales. Jaw fats contained few dietary lipids, but high concentrations of endogenously synthesized branched iso-acids. Lipid structure may influence sound flow from environment to ear, as sound travels faster through longer, straight hydrocarbon molecules than through shorter, branched chains. Porpoise fats were high in iso 5:0 (20-40%), but beaked whale samples were dominated by iso12:0 (20-50%). Porpoise fat compositions were consistent between internal and external depots. However, beaked whale jaw fats varied considerably intracranially. Iso12:0 concentrations were higher in internal than external fats. In a female beaked whale, internal jaw fats and ear fats had extremely high concentrations of iso10:0 (~10%) and iso12:0 (>30%). However, the jaw fats in her month-old calf contained very few iso-acids (<3%), being more typical of blubber lipids. Young odontocetes may have sound reception dependent hearing differences from adults, suggesting that echolocation requires both learning and physical development.

Computational Approaches to Biomimetic Sonar Modeling

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Use of a computational approach to the development of biomimetic sonar sources facilitates evaluation of a wide array of novel formations, theoretic mechanisms, and probing simulations. Computational analyses suggest that the biomechanical work required for click production increases modestly with increasing dive depth. We modified the Steinecke-Herzel model of the human larynx to incorporate a broad spectrum of empirical data to produce our computational model of dolphin click production. We used evolutionary computation techniques to explore the large parameter space of this model. To date, we have evaluated more than 2 million different configurations for their efficacy as biomimetic sonar sources. Our synthesis of empirical and computational results has culminated in a current effort to produce a prototype biomimetic sonar source. Deployment of biomimetic sources should be no more disruptive in the acoustic environment than an equal number of conspecifics.

Fish, Mollusks and Other Sea Animals' Use of Sound, and the Impact of Anthropogenic Noise in the Marine Acoustic Environment

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A preponderance of research on marine anthropogenic noise until recently has been

focused on the impacts and effects on marine mammals. This is largely due to the more common interaction of marine mammals with human enterprise such as fishing, aquaculture and cetacean oriented environmental legislation. While many studies over the past 50 years do examine the acoustical perceptions of other marine animals, this information has heretofore been mostly circulated among other bio-acousticians and applied to animal behavior and physiology studies. This overview paper excavates the existing literature on sound perception of fish, mollusks and cnidarians, extrapolating this data with human generation of sound in marine environments to frame a discussion on the potential impacts of anthropogenic noise in the sea.

Are All Fishes Created Equal?: The Differential Effects of Noise on Hearing

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Underwater noise and its potential deleterious impacts on marine and aquatic organisms have gained much attention recently. Despite this focus, data in many areas are lacking primarily due to a scarcity of appropriate models. This is especially the case for the auditory effects of underwater noise. Though fishes cannot be regarded as merely "small whales," they can be used to better understand many pertinent issues relating to underwater noise. One is the differential effect of underwater noise on hearing. In addition to marine mammals, not all fishes use sound identically or have equal auditory capabilities. Fishes can be broadly defined as hearing generalists (i.e. have a narrow frequency range with high thresholds) or hearing specialists (i.e. have ancillary structures that broaden frequency range and lower thresholds). Experiments were conducted using bluegill sunfish (Lepomis macrochirus), generalists, and fathead minnows (Pimephales promelas), specialists, exposed to intense white noise (142 dB re: 1 mPa, bandwidth 0.3-4.0 kHz) for various exposure duration (1-24 h). Auditory thresholds were measured immediately or after a period of recovery (1-14 days) and compared to control fishes using the auditory brainstem response (ABR) technique. Results and their ecological implications (i.e. predator-prey dynamics, management issues, etc.) will be discussed.

Studying the Hearing Capabilities of a Green Sea Turtle

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The New England Aquarium received a grant from the Office of Naval Research to study the hearing capabilities of threatened and endangered sea turtles. Since sea turtles inhabit all oceans, inshore as well as offshore, they are exposed to a wide variety of natural and human-made sounds. However, very little is known about hearing in sea turtles, and how sound effects their natural patterns of foraging, migrating, and reproduction.

Using operant conditioning, positive reinforcement, and a modified “Go/No-Go” experimental design, a 600 pound green sea turtle housed at the New England Aquarium has been taught to indicate when she hears a tone. Her frequency range and thresholds have been identified, and a masking study is in progress. This data provides the only behavioral information available for evaluating hearing in a sea turtle, and for assessing the impact of sound on sea turtles.

Of Manatees and Men: A Model for Understanding Acoustic Related Behavioral Phenomena and Designing Environmentally Friendly Solutions

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A comprehensive series of underwater psychoacoustic tests were conducted to measure the Florida manatees' hearing abilities and investigate their ability to detect and locate sounds of approaching vessels and other anthropogenic signals. The results yielded the audiogram, critical ratios, and directional hearing of various signals, while revealing sensory constraints that make manatees vulnerable to collisions with boats and barges. Complimentary to the behavioral measurements, underwater acoustic surveys of manatee habitats and noise propagation demonstrate significant Lloyd mirror and acoustical shadowing effects, further challenging acoustic detection of approaching vessels. Ironically, slow speed regulations designed to protect manatees increase collision risks in a majority of manatee habitats as ambient conditions mask the sounds of these vessels. Tests reveal that manatees can readily hear and localize higher frequency modulated sounds at levels just above ambient. This acoustic sensitivity provides a window through which manatees can be alerted of approaching vessels using very low intensity, directional signals. The interdisciplinary investigation of the boat strike problem has helped define the phenomenon and yielded a method of mitigation with minimal environmental impact. As the whales are also confronted with near surface propagation challenges in the sea, the approach may be applicable for addressing ship strikes and whales.

Mitigation of Ship Collisions with Whales by Enhancing Acoustic Awareness and Mediating Behavior

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The physics of near surface sound propagation can be crucial for detecting ship noise. Two prominent propagation phenomena can render whales vulnerable to collisions. The Lloyd Mirror effect, an embodiment of Snell's Law, and acoustical shadowing. The confluence of these effects, together with spherical spreading, and ambient masking, pose significant ecological challenges for detecting and locating approaching ships. A series of empirical measurements demonstrates large vessels can become acoustically indistinguishable from ambient noise. Quiet zones formed at the bows can become deceptive refuges that may actually attract whales. On-going measurements may soon result in directional acoustic solutions that "fill in" these shadows to alert whales. However, special projection techniques are necessary to selectively ensonify the near surface space and minimize near surface effects. Poor projection techniques can refract down and may cause whales to surface. Speed regulations proposed to reduce collisions are acoustically naïve, and could increase collision risks as noise intensity is proportional to the 5th power of speed (Lighthill's theory of aerodynamic sound). The relationship dictates that faster ships are detectable at significantly greater distances, allowing more time for whales to react. In multiple ship environments masking challenges are greatest and slow vessels can become acoustically undetectable.

Noise-induced Temporary Threshold Shift in Pinnipeds: Effects of Exposure Medium, Intermittence, Duration, and Intensity

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We assessed noise-induced temporary threshold shift using behavioral psychophysics in individuals representing three pinniped species: California sea lion, harbor seal, and northern elephant seal. The fatiguing stimulus was an octave band of noise centered at 2500 Hz. Noise and tones were presented aerially (continuous exposure), or under water (intermittent exposure). Exposure levels ranged from 137 to 174 dB re: 1µPa under water and 68 to 124 dB re: 20µPa in air. Maximum threshold shifts ranged from 12 to 28 dB. There were no differences between threshold shifts measured in air vs. under water, when intermittency was equated. For two subjects, there were significant positive relationships between threshold shifts and noise energy flux density and log of exposure duration. These relationships were consistent for both intermittent and continuous exposure conditions. Based on these results, we conclude that 1) growth of threshold shift in pinnipeds should be modeled using the sound energy of the fatiguing stimulus as a factor; 2) noise exposures sufficient to induce TTS are approximated by a 5-dB exchange rate (intensity per doubling of exposure time); 3) in-air TTS testing is a robust method for assessing the harmful effects of underwater and airborne noise on amphibious animals.

Temporary Threshold Shift (TTS) Measurements in Bottlenose Dolphins *(Tursiops Truncatus)*, Belugas *(Delphinapterus Leucas)*, and California Sea Lions *(Zalophus Californianus)*

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Intense anthropogenic underwater sound may adversely affect the hearing and behavior of many marine mammals. Exposure to intense sound may produce an elevated hearing threshold, also known as a threshold shift (TS). If the threshold returns to the pre-exposure level after a period of time, the TS is known as a temporary threshold shift (TTS). Marine mammal TTS studies at SSC San Diego have examined the effects of pure tones and underwater impulsive waveforms on bottlenose dolphins, belugas, and California sea lions. In these studies, a behavioral response paradigm is used to measure hearing thresholds before and immediately after exposure to high-intensity underwater sound. This paper reviews the TTS studies conducted at SSC San Diego, including the test methodology, sound exposure parameters, and the results. Particular attention will be given to current efforts, which are focused on the effects of mid-frequency tones on bottlenose dolphins. Preliminary data will be presented for the growth of TTS as a function of SPL and duration for single frequency tones.

ABRs Measuring Hearing During TTS and Echolocation

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The time course of recovery from temporary threshold shift (TTS) was measured in a bottlenose dolphin *Tursiops truncates* using an evoked-potential technique. The envelope-following response (EFR) which is a rhythmic train of auditory brainstem responses (ABR) to sinusoidally amplitude-modulated tones, was used as an indicator of the sound perception by the subject. The variation of stimulus intensity allowed the measurement of EFR thresholds. During each session, following an initial measure of threshold, the trained animal voluntary positioned within a hoop 1 m underwater while 160 dB re 1 ìPa noise of a 4–11 kHz bandwidth was presented for 30 minutes. After the noise exposure, thresholds were measured again at delays of 5, 10, 15, 25, 45, and 105 min. Measurements were made at test frequencies of 8, 11.2, 16, 22.5, and 32 kHz. Maximum TTS occurred 5 min after exposure and rapidly recovered with a rate of around 1.5 dB per time doubling. TTS occurred at test frequencies of 8 to 16 kHz, the maximum at 16 kHz; TTS was negligible at 22.5 kHz and absent at 32 kHz.

Auditory Brainstem Responses of Multiple Species of Sea Turtles

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Sea turtles may be impacted by anthropogenic noise in the oceans. However, little is known about either their hearing abilities or the importance of sound cues. Moreover, sea turtles occupy different habitats during each developmental stage. Thus, both habitat and differences in gross morphometry of auditory structures are confounding variables. In this project, we are examining the hearing system of multiple size classes and species of sea turtles using auditory brainstem response (ABR) techniques. ABRs occur within the first 10 ms following the presentation of sound stimulus and consist of identifiable waves associated with the sequence of auditory events in the brainstem. In this experiment, subdermal electrodes were implanted on one side of the fronto-parietal plate and a reference electrode was inserted in inactive skin. Using Tucker Davis Technologies system, we delivered a stimulus of known frequency to a sound source located above the turtle and recorded evoked neural responses. To date, we have recorded ABRs from Kemp`s ridley (*Lepidochelys kempi*), green (*Chelonia mydas*), and loggerhead (*Caretta caretta*) sea turtles. These turtles detected frequencies between 100 and 1000 Hz. This project will provide the first multi-species/multi-age in vivo experimental measures for estimating the potential impact of sound on sea turtles.

Experimental Measures of Blast Trauma in Marine Mammals

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Ears are the most pressure sensitive mammalian tissues, but cetacean and land mammal ears differ in stiffness, mass, vascularization, and pneumatization. Therefore, we cannot arbitrarily extrapolate underwater mitigation zones from land mammal responses. Rosowski et al, (1990, Ann. Otol. Rhin., Laryn.) showed live and post-mortem ears have isomorphic mechanical properties. Blast traumas are essentially mechanical responses, therefore blast effects are inducible and measurable in post-mortem specimens. In this study, post-mortem specimens were subjected to controlled blasts to determine how mechanical damage to ears and major organs varies with received peak pressure. Stranded animals euthanized for medical reasons were implanted with pressure gages, CT scanned, and exposed to underwater blast pressures of 10-300 psi. Following exposures, specimens were rescanned and necropsied by a team of mammal blast specialists who were blinded to test pressures. All procedures were documented by UW video and still photography Analyses of 20 test and control specimens show both the severity and number of impacts are mass-dependent and correlated with received psi. Further, some organs unique to cetaceans; e.g., blubber, jaw fats, and melon, have distinct damage patterns that may provide diagnostic markers in suspected UW blast cases. Supported by ONR contract N00014-97-11030.

Appearance of Odontocete Respiratory Tissues After Exposure to Blast Pressures

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The odontocete respiratory tract is adapted to withstand the gradual pressure changes associated with diving, yet nothing is known about how it responds to the sudden pressure changes of a blast exposure. Our goal is to characterize any respiratory injuries resulting from postmortem blast pressure exposures. Tissues were harvested from 14 freshly dead odontocetes obtained from naturally occurring strandings and artificially exposed to blast pressures post mortem (supplied by D. Ketten). Blast pressure exposure levels were not revealed to enable unbiased observations. Results indicate that many specimens show dark reddish discoloration of variable intensities that may be evidence of blast-induced trauma. Discoloration was found in the lungs (striped pattern correlating with ribs), larynx (above and below palatopharyngeal sphincter), trachea (uniform throughout lumen), and nasal region (visualized only in areas of sloughed lining). Gas containing tissues may exhibit damage due to dramatic compression/expansion to accommodate changing gas volumes. Abrupt edges to discoloration patches indicate protection, possibly conferred by contact with adjacent tissues. Discoloration patterns are consistent in location but have variable intensity, perhaps reflecting different degrees of exposure. This information may be useful in setting critical exposure limits to prevent harm to odontocetes in the vicinity of a blast event.

The Relationship of Anthropogenic Noise and Sperm Whale Sound Production

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The relationship of anthropogenic noise and sperm whale (*Physeter macrocephalus*) sound production is examined in order to understand better the effects of anthropogenic sound on sperm whale behavior. Three recording systems were moored in the Gulf of Mexico 50 feet from the ocean floor at depths of 600 m, 800 m, and 1000 m in a line spanning 25 km at sites where sperm whales were known to congregate. Sounds were recorded at an 11,718 Hz sampling rate for 36 consecutive days. The recordings revealed considerable amounts of anthropogenic noise, as well as frequent sperm whale clicks. The anthropogenic noise consisted primarily of sounds produced by ships or seismic exploration air guns. Different levels of ship noise were found, varying from none to very intense. It is possible that intense ship noise might affect sperm whale click production, particularly if the whales cannot hear clicks or perceive returning echoes during these times. Less intense noise did not seem to affect click production, suggesting that the whales had adapted to such levels of noise. Acoustic propagation models are used to simulate received broadband whale clicks. Comparison of experimental and modeled data aids interpretation of features in the spectra of received signals.

Determining Source Levels and Sound Fields for Singing Humpback Whales *(Megaptera Novaeangliae)* on The Hawaiian Wintering Grounds

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Male humpback whales (*Megaptera novaeangliae*) on their wintering grounds produce complex vocalizations termed “song.” The stereotypical stationary posture adopted by singers suggests they are attempting to optimize transmission range. In March 2002, we measured the sound fields of singers using divers equipped with rebreather scuba. A custom-designed ‘Aquahead’ system reliably located

singers to within 30 m. Fourteen singers were located from as far away as 8.2 km and in times of 11-48 min. The rebreathers enabled divers to descend to the singer with minimal expulsion of bubbles and noise. Divers moved in arcs around the singer to sample song at various orientations using digital video cameras while simultaneously measuring depth and range to the singer's head using handheld ultrasonic range meters. At the end of a song a snorkeler used our videogrammetric technique to measure singer body length. Initial signal processing of five singers indicates source powers of up to 190 dB re 1 microPa @ 1 m with a directionality oriented in front of the singer's head, lateral power levels being up to 18 dB below those in front at some frequencies. Higher frequencies were observed to have a higher directionality than lower frequencies.